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The Resistance of Some High Strength Steels to Slow Crack Growth in Salt Water

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13. ABSTRACT

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values for crack growth in salt water of some high strength steels are given. A number
of martensitic, maraging, and precipitation-hardening steels over a range of yield
strengths are included.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
High strength steels						
Maraging steels						
Martensitic steels						
Precipitation-hardening steels						
Stress corrosion						
Stress-corrosion cracking						
Stress intensity						
Threshold stress intensity						

CONTENTS

Abstract

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Status

Concluding report on this phase of the program.

Authorization

NRL Problem M04-08A
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INTRODUCTION

The characterization of high strength steels with respect to resistance to stress corrosion cracking (SCC) in seawater has been a goal of the Naval Research Laboratory. The results of these determinations are presented here. A discussion of some of the problems encountered in obtaining or in interpreting the data follows.

PROCEDURE

The data were obtained using precracked specimens stressed in the cantilever-beam test of Brown.[1] In most of the tests distilled water containing $3\frac{1}{2}$ pct NaCl was used as the corrodent, but some tests were run in flowing seawater at Key West, Florida, to compare the effects of the two environments.

The steels studied were mostly 1-in. plates of commercial martensitic, maraging, and precipitation-hardening types. The dimensions of the specimens were as large as the 1-in. plate thickness would allow for a through-the-thickness direction of crack propagation (WT and RT).* For certain tests on the effects of orientation and in some cases where 1-in. plate was not available, specimens were tested in the RW or WR* directions. These specimens were cut to a depth of 1 in. to correspond as closely as possible to the WT and RT specimens.

Specimen width was designed to satisfy as closely as possible the requirements of plane strain conditions; in all cases except where the experiments were designed otherwise, the plane strain requirements were believed to be met at the stress intensity levels near K_{Iscc}.

The values of the dry fracture toughness parameters reported for the steels are either the K values which approximate K_{Ic} reported by Stonesifer and Smith,[2] or the values of K_{Ix} obtained by loading dry specimens to fracture in the cantilever-beam apparatus. Both parameters are guides and not absolute plane-strain fracture toughness numbers.

The effects of direction of stress corrosion crack propagation in the plates were not great, as the data will

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* ASTM Committee E-24 convention. The orthogonal axes in a plate are fixed as rolling direction (R), transverse direction (W), and plate thickness (T). The first letter in the convention specifies direction perpendicular to the fracture plane; the second letter specifies the direction of crack growth.

show. The bulk of the data, however, was obtained with WT
type specimens. No data were obtained with through-the-
thickness fractures of the TR or TW type. The convention
used to indicate fracture orientation with respect to
wrought texture is that of ASTM Committee E-24.

RESULTS

The results for some individual classes of steel will be
presented, preceding the final composite illustrations.
This will clarify the relations between the fracture tough-
ness index (K_{Ic} or K_{Ix}) or the SCC index (K_{Iscc}) with yield
strength in each steel class. Variations in K_{Ic} and K_{Iscc}
among different heats of given steel classes at a given
yield strength level will also become apparent.

AISI 4340

The variation of K_{Ix} and K_{Iscc} with yield strength of two
heats of quenched-and-tempered AISI 4340 steel is shown in
Fig. 1. As indicated, one of these heats was in the form
of a billet; the other, a plate. The values of K_{Iscc}
decline in each case with increasing yield strength, and
the values of plate and billet are not markedly different.
The major difference noted is that the apparent dry fracture
toughness of the billet is considerably higher than that
of the plate, and does not decrease with increasing yield
strength as is the case with the plate. No explanation
for the difference is known.

9Ni-4Co-C

The results for quenched-and-tempered 9Ni-4Co-0.25C and
9Ni-4Co-0.20C steels are given in Figs. 2 and 3, respectively.
The K_{Ic} and K_{Ix} values of the 0.25C steel vary between 140
and 190 ksi$\sqrt{\text{in}}$.; the values of K_{Iscc} between about 70 and
110 ksi$\sqrt{\text{in}}$. The values of K_{Ix} and K_{Iscc} for the 0.20C
steel fall within but near the upper limits of the K_{Ic} and
K_{Iscc} values of the 0.25C steel.

12Ni Maraging

The 12Ni maraging steels were tested in the 150 to 190 ksi
yield strength range. The results, Fig. 4, show a consider-
able range in both the K_{Ic} or K_{Ix} and K_{Iscc} values, but
the optimum values for each yield strength show a trend
toward lower values of K_{Iscc} with increasing yield strength.
The wide range of K_{Ic} or K_{Ix} and K_{Iscc} values obtained shows
that steels of the same nominal composition and heat treated
to about the same yield strength may vary markedly in
resistance to SCC and, to a lesser extent, in fracture

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strength. The three lowest values of K_{Iscc} plotted in Fig. 4 are known to be accounted for by improper heat treatment, but the other values of K_{Iscc} probably reflect the variability to be normally expected in these steels.

18Ni Maraging

The 18Ni maraging steels were available and were tested at a range of yield strength levels, varying from 170 to 260 ksi. The results, Fig. 5, show that K_{Ic} or K_{Ix} and K_{Iscc} decline as the yield strength increases. There is apparently a fairly constant difference between the K_{Ic} and K_{Iscc} values of from 20 to 40 ksi$\sqrt{In}$. The possibility of improvements in the K_{Iscc} values in these alloys, therefore, appears to be limited until the dry fracture toughness of the steels can be improved, particularly at the higher strength levels.

13Cr-8Ni-Mo-PH

This alloy was tested over a yield strength range of 130 to 210 ksi obtained by heat treatment. It was found, Fig. 6, that the values of K_{Ic} or K_{Ix} and K_{Iscc} are high until the 200 ksi yield strength level is reached. At this point the value of K_{Iscc} drops, and the value of K_{Ix} is significantly lower than the values of K_{Ic} for the lower yield strength alloys. There are not large differences between K_{Ic} or K_{Ix} and K_{Iscc} at any strength level observed; hence, the alloy is quite resistant to SCC. Certain complicating features will be discussed in a later section.

The results above plus the results on some other steels are presented collectively in Figs. 7 and 8. In Fig. 7, where K_{Iscc} is plotted against K_{Ic} or K_{Ix}, it is obvious that if there is total resistance to SCC, K_{Iscc} equals K_{Ic} or K_{Ix}, and the points must fall on a line 45 deg to each axis. A steel is susceptible to SCC to the extent that the K_{Iscc} value falls below the 45 deg line.

Figure 7 shows that in the lower ranges of fracture toughness, the quenched-and-tempered low alloy steels are quite good, but these steels do not reach the higher toughness range. The steels which resist SCC and reach higher levels of toughness are the higher alloy steels. There does not, however, appear to be any clear-cut advantage of one high alloy steel over another. The importance of the details of melting, fabricating, and heat treating the high alloy steels is again seen in the wide spread of K_{Iscc} values in the 120 to 270 ksi$\sqrt{In}$. range of K_{Ic} values. Thus high alloy steels if treated improperly are no better than carbon steels.

In Fig. 8 the values of K_{Iscc} are plotted against the yield
strength values. The low alloy carbon steels are good at
the low yield strength range but become highly susceptible
as the yield strength approaches 200 ksi. The K_{Iscc} values
of the highly alloyed steels also fall off rather abruptly
with increasing yield strength, but at higher values of
K_{Iscc} and yield strength. The wide range of values among
the high alloy steels in the 160 to 200 ksi yield strength
range is again evident.

The lines in Fig. 8 show the condition under which infinitely
long surface flaws of given depth will grow in the steels
stressed to the yield point. Thus a higher K_{Iscc} value
permits larger flaws to be tolerated at a given stress level.
At a given value of K_{Iscc}, however, the tolerable flaw size
decreases with increasing yield strength.

INTERPRETATION OF DATA

In obtaining the data presented above certain problems were
expected and sometimes encountered. A discussion of some
of the more important considerations follows:

Directionality

It has been recognized that SCC susceptibility may depend
on direction of crack propagation with respect to the rolling
direction and thickness of a plate. Certain aluminum alloys
are known to be highly directional in this respect according
to Puzak et al.[3] Insofar as can be determined from the
present work, however, there are no great directional effects
among the steels. Table 1 summarizes tests for K_{Iscc} on
four steels run in various orientations. The differences
noted are small.

Environment - Seawater vs $3\frac{1}{2}$ percent Salt Water

Tests by Sandoz and Newbegin[4] comparing the K_{Iscc} values of
4340 steels in distilled water containing $3\frac{1}{2}$ percent NaCl
and in flowing seawater at Key West, Florida, indicate
(Fig. 9) that the differences are small. Other tests by
Leckie and Loginow[5] indicate that natural flowing seawater
is more aggressive than artificial seawater on HY-130 (T),
12Ni maraging steel (176 ksi yield strength), and 18Ni
maraging steel (252 ksi yield strength). The differences in
terms of effects on K_{Iscc} were also small in these tests,
however. It is concluded that the results of laboratory
tests for the K_{Iscc} values of steels conducted in distilled
water containing $3\frac{1}{2}$ percent NaCl approximate the results of

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similar tests in flowing seawater (in the absence of cathodic protection systems which may contaminate stagnant solutions.)

Double Cracks (Crack Branching)

In certain steels, propagating stress corrosion cracks tend to branch, and this complicates the interpretation of any calculation of the stress intensity factor. The 9Ni-4Co alloys are particularly susceptible to this phenomenon.

Figure 10 shows a branched stress corrosion crack emanating from the tip of the fatigue crack in one such sample. At least one study and analysis of this crack branching has been conducted.[6] As for the data presented here, samples with multiple cracks were discarded.

Crack Initiation Site

In some cases with the 13Cr-8Ni-Mo precipitation-hardening alloy, crack initiation occurred near the junction of the container for salt water and the specimen, and not at the tip of the fatigue crack. Figure 11 shows one sample where such a crack initiated and propagated, leaving the fatigue crack unchanged. The crack which did initiate did so only after hundreds of hours of testing. The reason is believed to be that the solution is more confined just under the rubber seal and that an acid solution develops more readily there than in the fatigue crack which is stressed open and in a vertical position.

For the data presented here only specimens which did behave in the normal way were considered valid.

Type of Loading

Among the values of K_{Iscc} presented, some were obtained by the step-loading process to conserve specimens. This involves loading a single precracked specimen to progressively higher levels of stress intensity until finally slow crack growth takes place. The K_{Iscc} values so obtained have been generally found to be about equal to the K_{Iscc} values found by using new specimens for each stress intensity. In the case of the 12Ni maraging steel, however, it has been demonstrated by Sandoz and Newbegin[7] that step loading can lead to gross errors. Thus as Table 2 shows, samples may be "nursed" upward to stress intensity values as high as 170 ksi$\sqrt{\text{in}}$. by step loading without developing stress corrosion cracks, whereas the same samples of material loaded directly will crack readily at a stress intensity as low as 50 ksi$\sqrt{\text{in}}$.. The reason for this is that the extended

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exposure to salt water causes the fatigue crack to blunt at a stress intensity less than critical because of crevice corrosion, as in Fig. 12. Obviously the effects of step loading must be checked out for each type of steel before the data from such tests can be accepted. This has been done for the data in this paper.

Section-Size Effects

It is implicit in most presentations of K_{ISCC} data that plane-strain conditions exist, at least at the stress intensity level required by K_{ISCC}. It is believed that essentials of plane-strain conditions were usually met in the tests run to obtain the data presented here.

Nevertheless cases arise where the thickness of the plate or the capacity of the testing machine prevent plane strain from being achieved, at least in the strict sense of Brown and Srawley.[8] There is some evidence now, however, that at least in some cases the importance of plane-strain conditions in K_{ISCC} testing has been overestimated. Tests by Sandoz and Newbegin[9] in a titanium alloy, for example, have shown little effect of section size (B dimension) in the cantilever-beam-type specimen. And tests on 12Ni maraging steels in the present investigation have shown the same. The results of variation of the B dimension between 0.1 in. and 1.0 in. are shown in Figs. 13 and 14. It is seen readily in Fig. 13 that there is no decrease in K_{ISCC} with increasing specimen breadth. If anything, the thin specimens have the lowest K_{ISCC} values.

The apparent scatter in the data in Figs. 13 and 14 can be visualized as a reversal effect, i.e., at some intermediate stress intensity level specimens break in shorter time than they do at somewhat higher or lower stress intensity levels. The dotted lines in Figs. 13 and 14 show how such a reversal could account for all the test results. Thus in Fig. 13 at stress intensity levels of about 90 ksi$\sqrt{\text{in}}$., the 0.10-in.-thick specimens last for over 1000 hours, but break in less than 200 hours when the stress intensity is around 70 ksi$\sqrt{\text{in}}$. Stress intensities higher than 90 ksi$\sqrt{\text{in}}$. again produce shorter times for a crack growth and fracture.

The reversals seen were expected in the belief that a change from essentially plane strain to a non-plane-strain condition would take place in some specimens with increasing stress intensity. This was expected to produce a break in the stress intensity-time to fracture curve. However, there is obviously no connection between the reversal and the section size (B dimension) of the specimens.

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The reversal is suspected to be related to the crevice corrosion within the fatigue crack tip in a manner similar to the type of corrosion noted earlier during the step loading of 12Ni maraging steel (see Fig. 12). Perhaps at intermediate values of stress intensity the crack is opened just enough to permit crevice corrosion to take place and blunt the crack. At lower values of stress intensity the confined fluid may more readily develop the acidity essential for the stress corrosion crack to initiate and propagate according to Brown, Fujii, and Dahlberg.[10] At higher values of stress intensity there is some tearing, and the stress is high enough to propagate a crack without as much corrosion.

In any case the reversal shown is probably restricted to certain alloys such as the 12Ni maraging steel, and the value of K_{ISCC} selected from the data is not much affected by it (the upper and lower threshold values are close).

SUMMARY AND CONCLUSIONS

Some data obtained at the Naval Research Laboratory on the SCC susceptibility of steels are presented. Some of the problems encountered in obtaining the data and the considerations involved in interpreting the test results are then reviewed.

The conclusion is that the SCC resistance of steels generally increases as one progresses from the low alloy steels to the high alloy steels, particularly at the higher levels of yield strength. There is no basis, however, for the choice of a particular class of high alloy steel because of the apparent effects of processing variables.

ACKNOWLEDGMENT

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Table 1

Effects of Specimen Orientation
with Respect to Wrought Texture on K_{Iscc}
(The convention used is that of ASTM Committee E-24)

Alloy	K_{Iscc} (ksi$\sqrt{\text{in.}}$)			
	RT	WT	WR	RW
9Ni-4Co-0.2C		115	104	
18Ni-180		125	1.	
12Ni-5Cr-3Mo		19	19	25
12Ni-5Cr-3Mo	70	60		
12Ni-5Cr-3Mo		105	103	
4340 (200 YS)			11	10

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Table 2

Effect of Step Loading and Direct Loading on the Stress
Intensity Factor for Subcritical Crack Growth of
12Ni-5Cr-3Mo Maraging Steel in Salt Water

Specimen No.	Step Load		Direct Load	
	K_i	Hours to break	K_i	Hours to break
J5	179	0.5	146	17
	168	100 NB		
J71	171	50 NB	51	125
J72	165	180 NB	49	8

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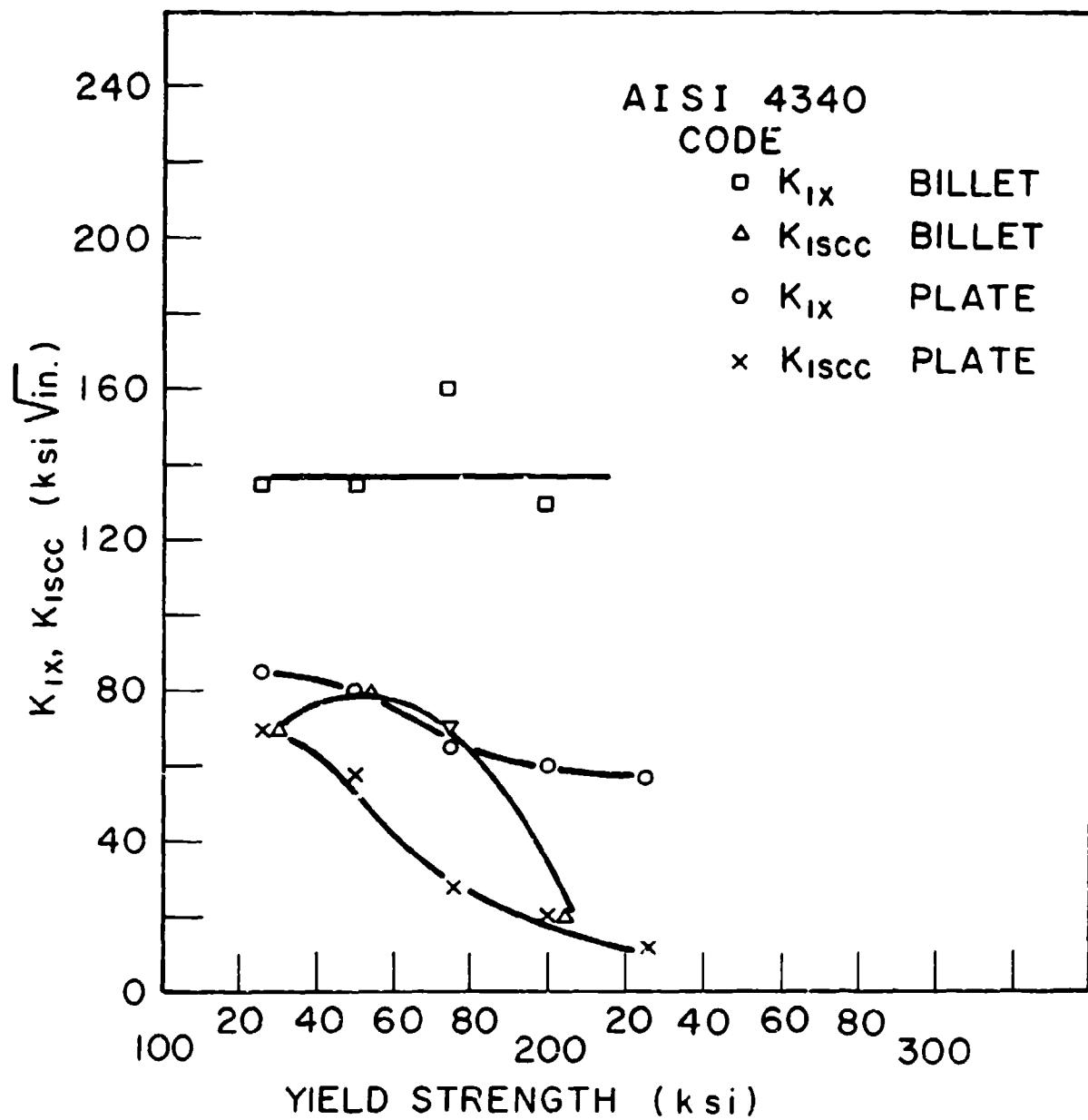
Fig. 1 – Threshold stress intensity parameter values for crack growth in AISI 4340 steel, dry (K_{Ix}) and in salt water (K_{Iscc}), as related to yield strength.
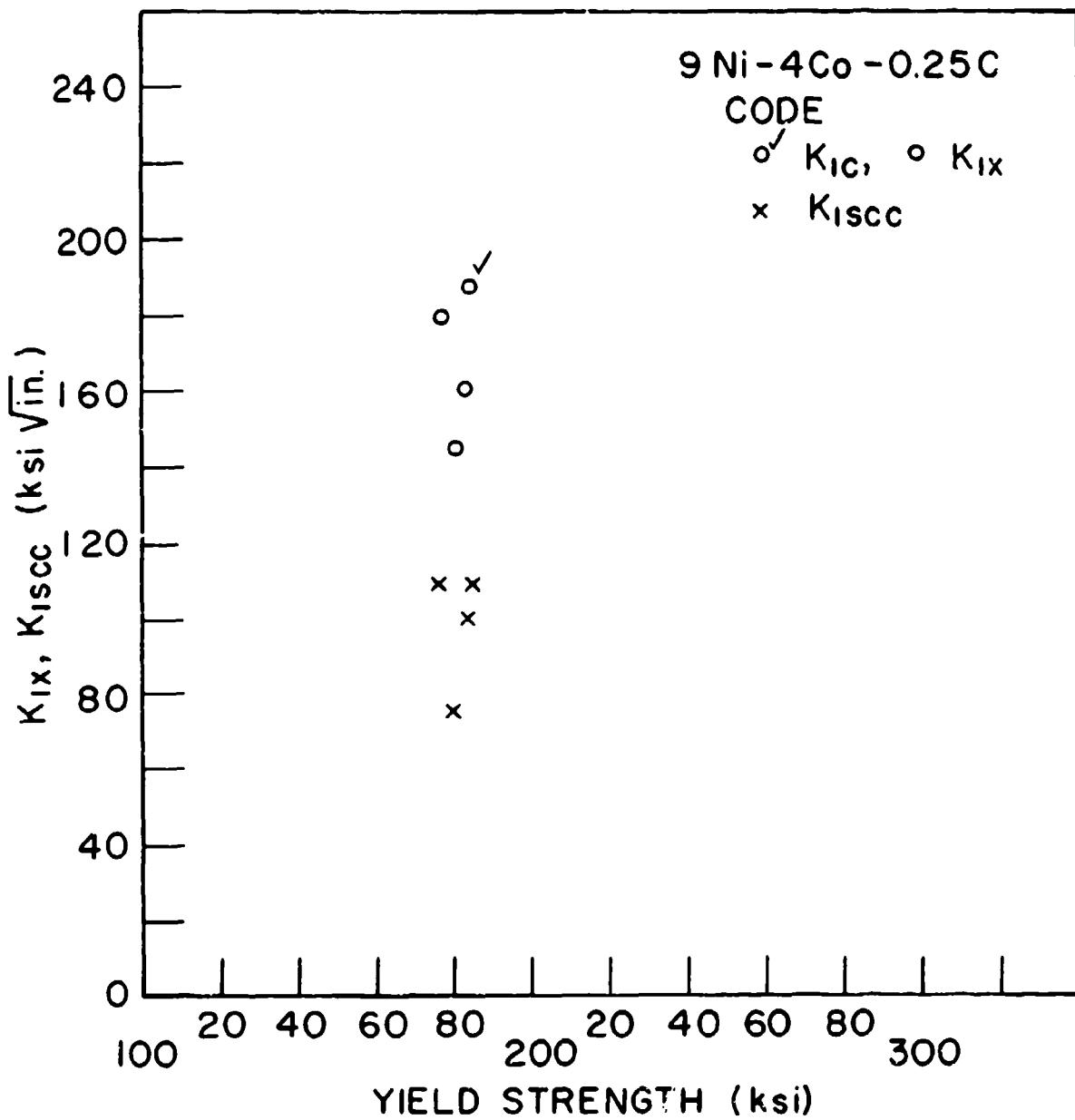
Fig. 2 - Threshold stress intensity parameter values for crack growth in 9Ni-4Co-0.25C steel, dry (K_{Ix} or K_{Ic}) and in salt water (K_{Iscc}), as related to yield strength.
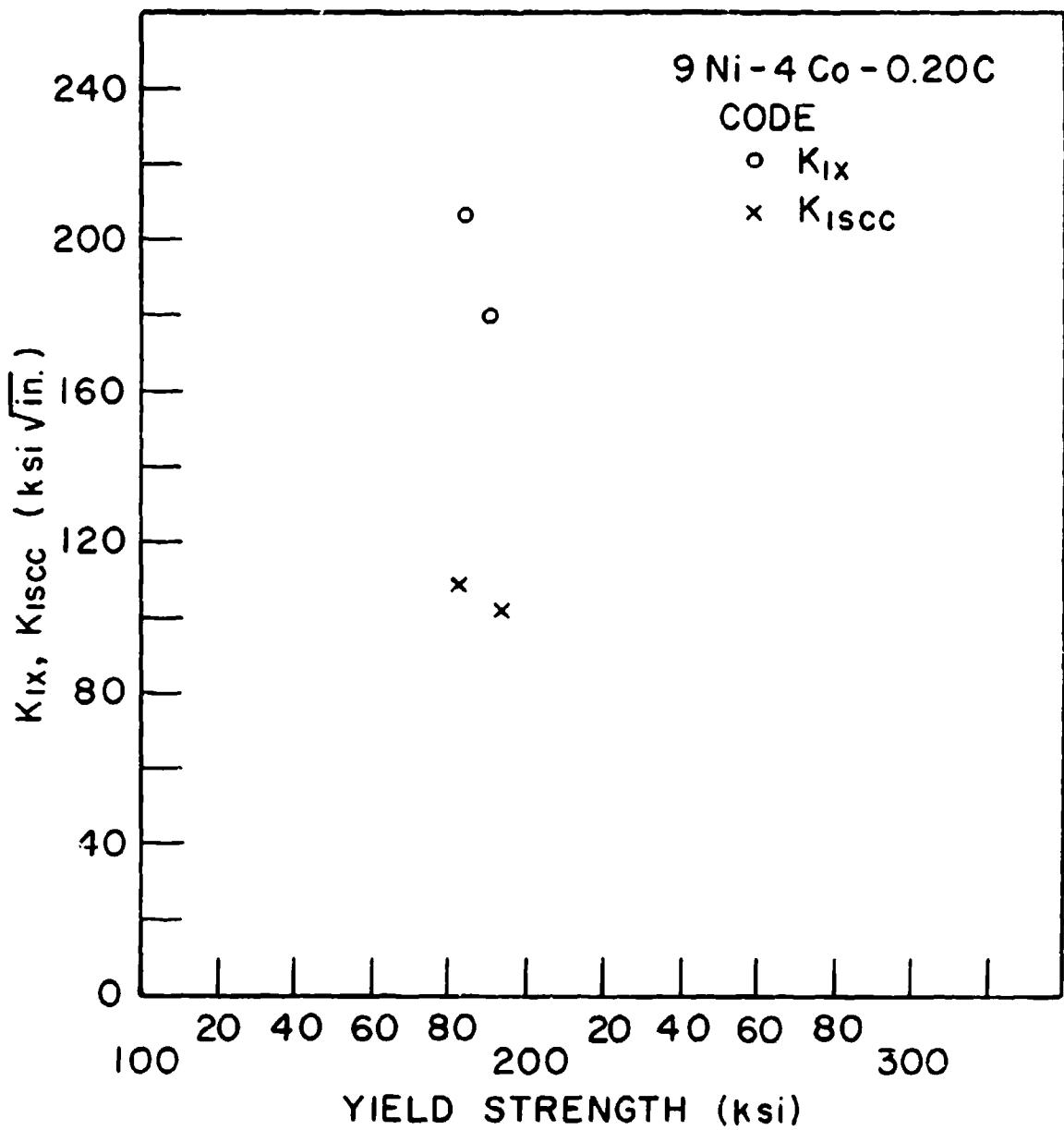
Fig. 3 - Threshold stress intensity parameter values for crack growth in 9Ni-4Co-0.20C steel, dry (K_{Ix}) and in salt water (K_{Iscc}), as related to yield strength.

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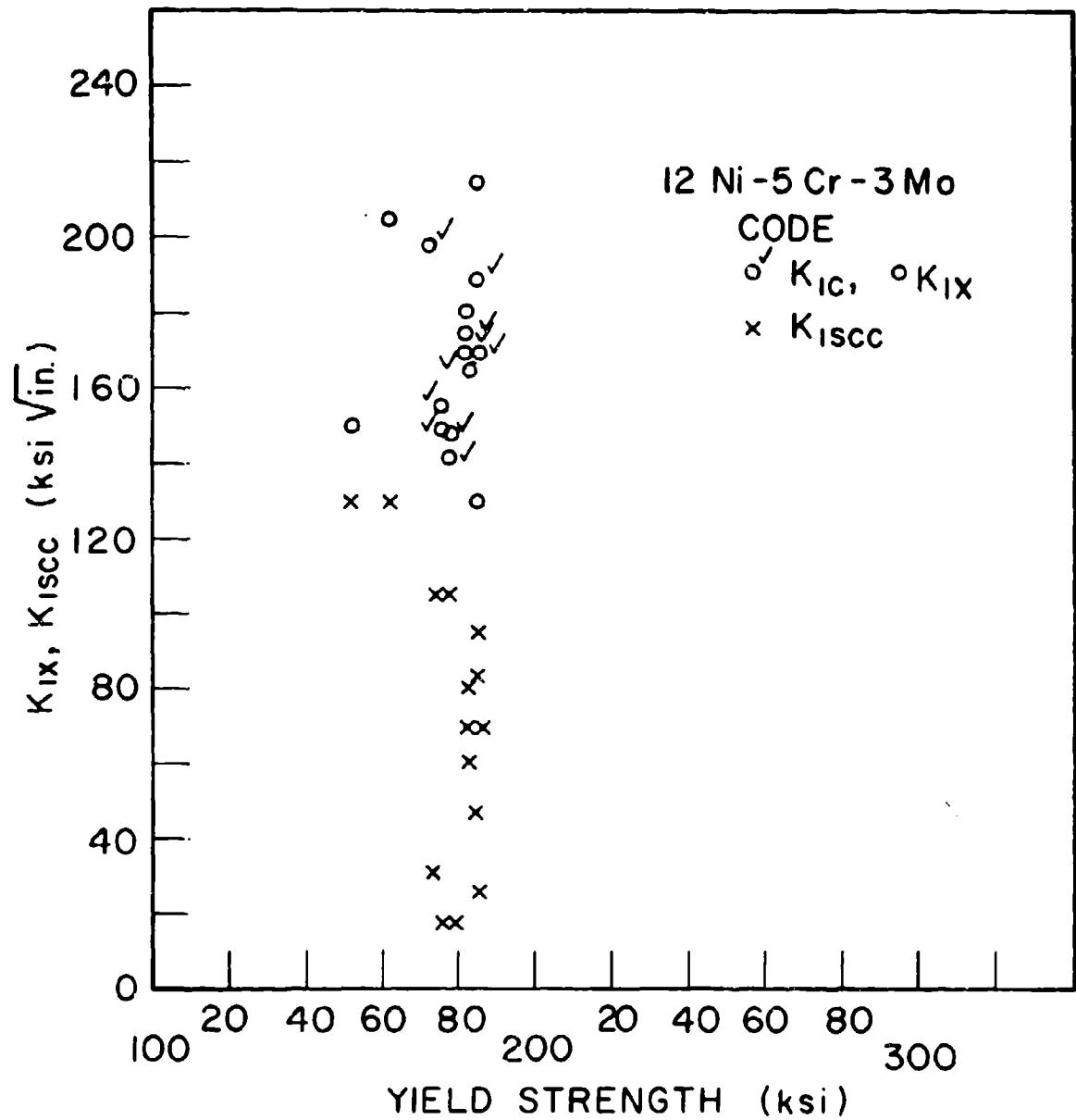
Fig. 4 – Threshold stress intensity parameter values for crack growth in 12Ni-5Cr-3Mo maraging steel, dry (K_{Ix} or K_{Ic}) and in salt water (K_{Iscc}), as related to yield strength.

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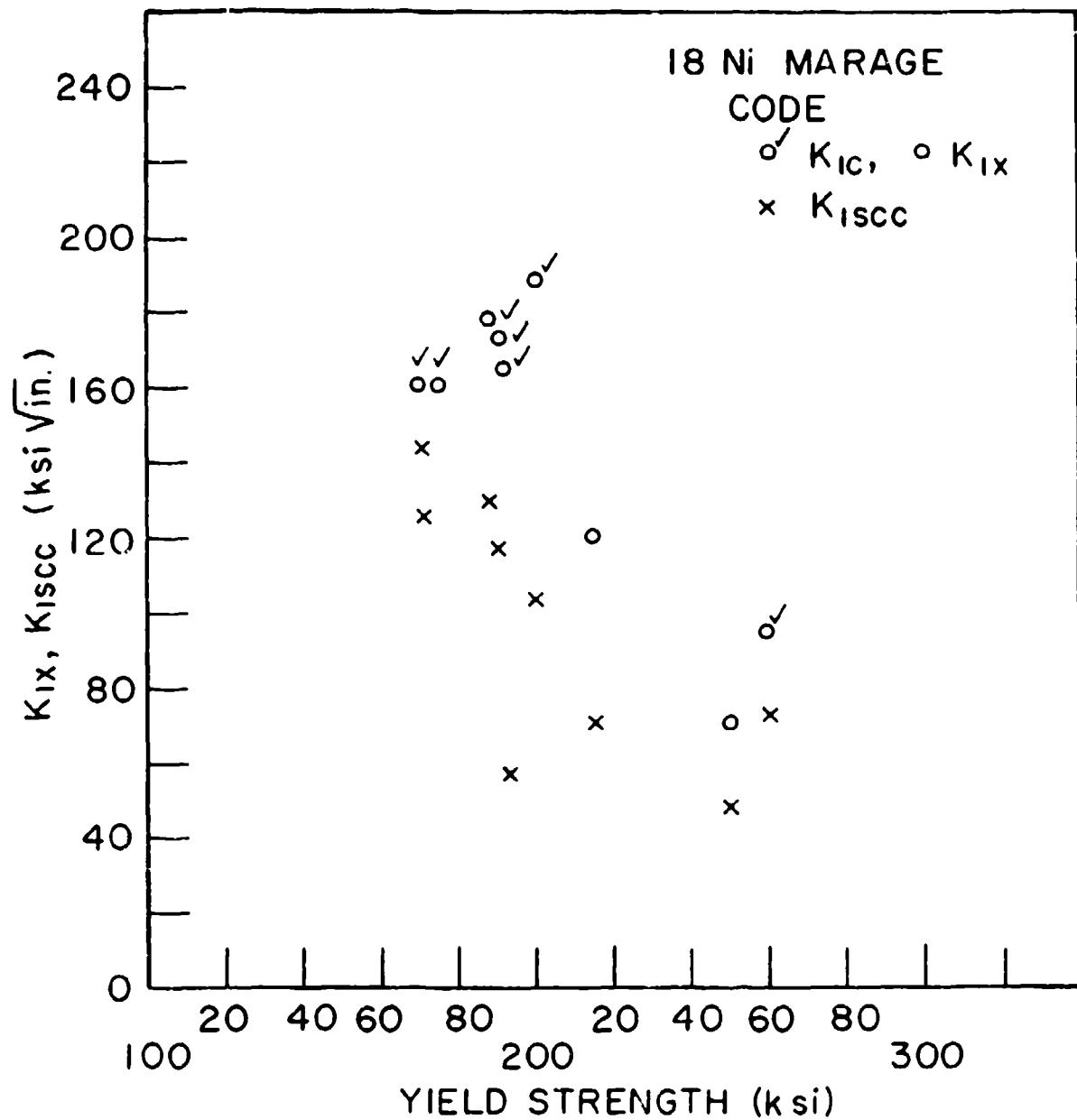
Fig. 5 – Threshold stress intensity parameter values for crack growth in 18Ni maraging steel, dry (K_{Ix} or K_{Ic}) and in salt water (K_{Iscc}), as related to yield strength.

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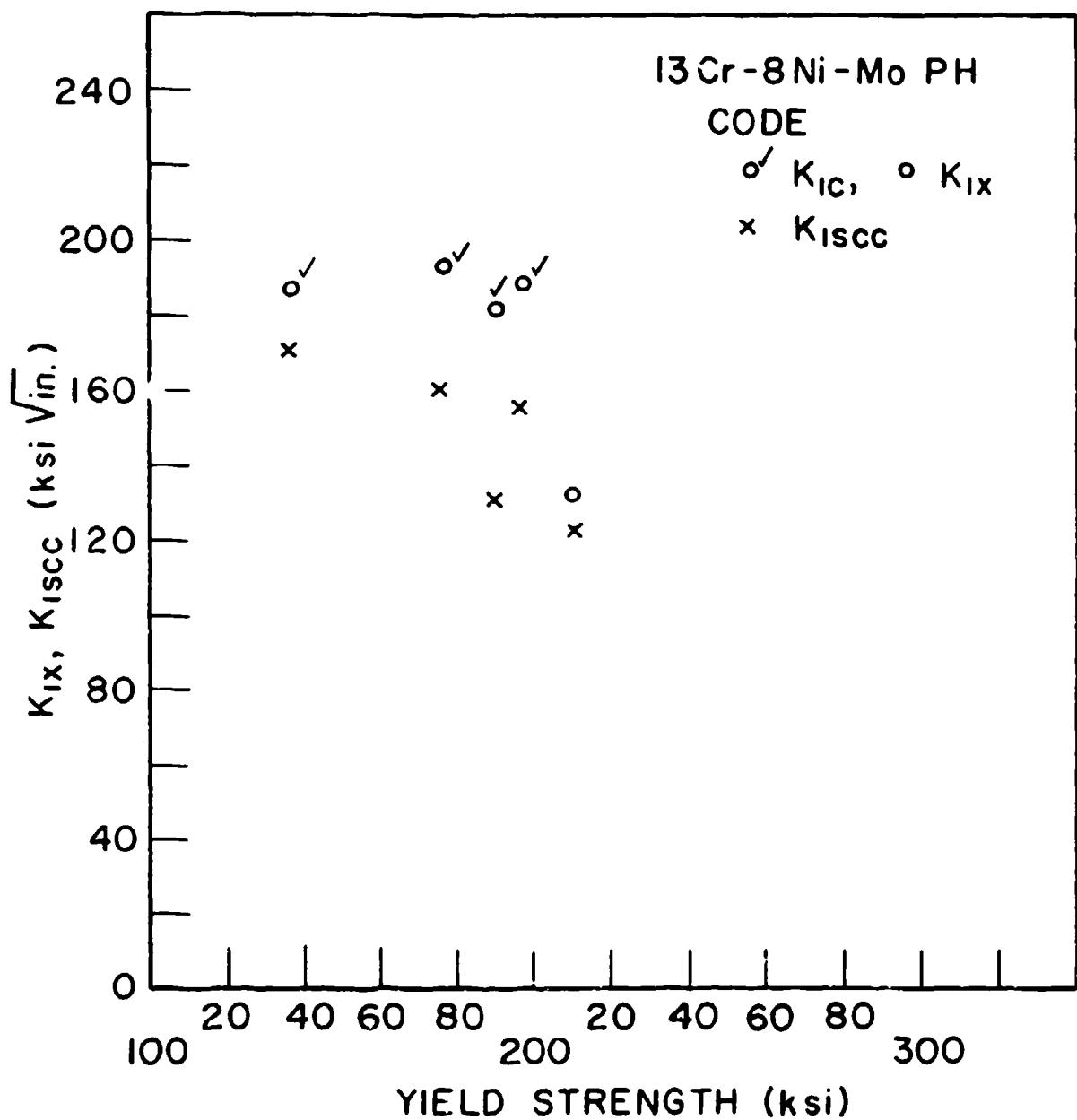
Fig. 6 - Threshold stress intensity parameter values for crack growth in 13Cr-8Ni-Mo-PH steel, dry (K_{Ix} or K_{Ic}) and in salt water (K_{Iscc}), as related to yield strength.
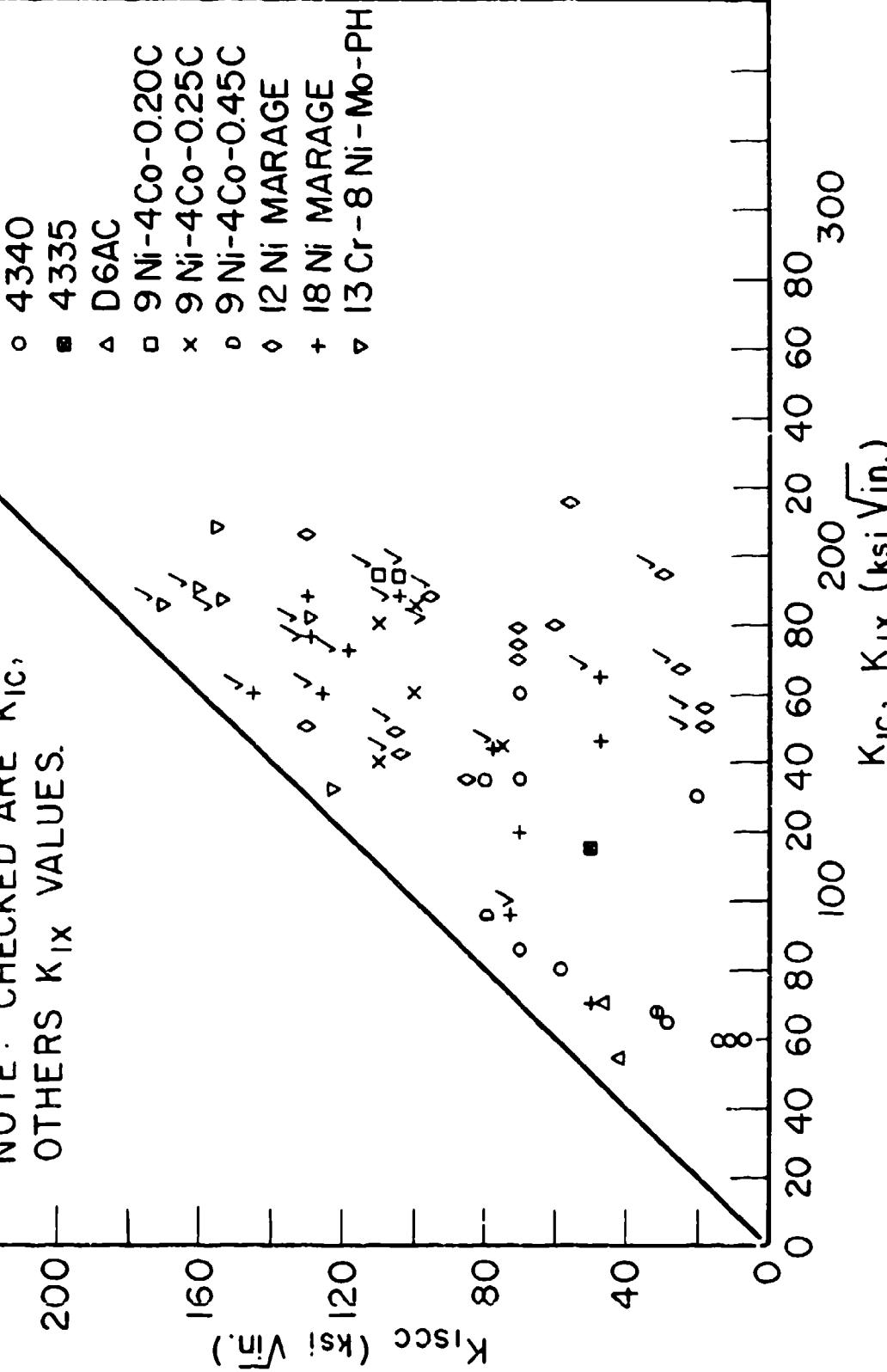
Fig. 7 – Composite of the relation between fracture toughness (K_{Ic} or K_{Ix}) and the threshold stress intensity for stress corrosion (K_{Iscc}) of a number of commercial steels.
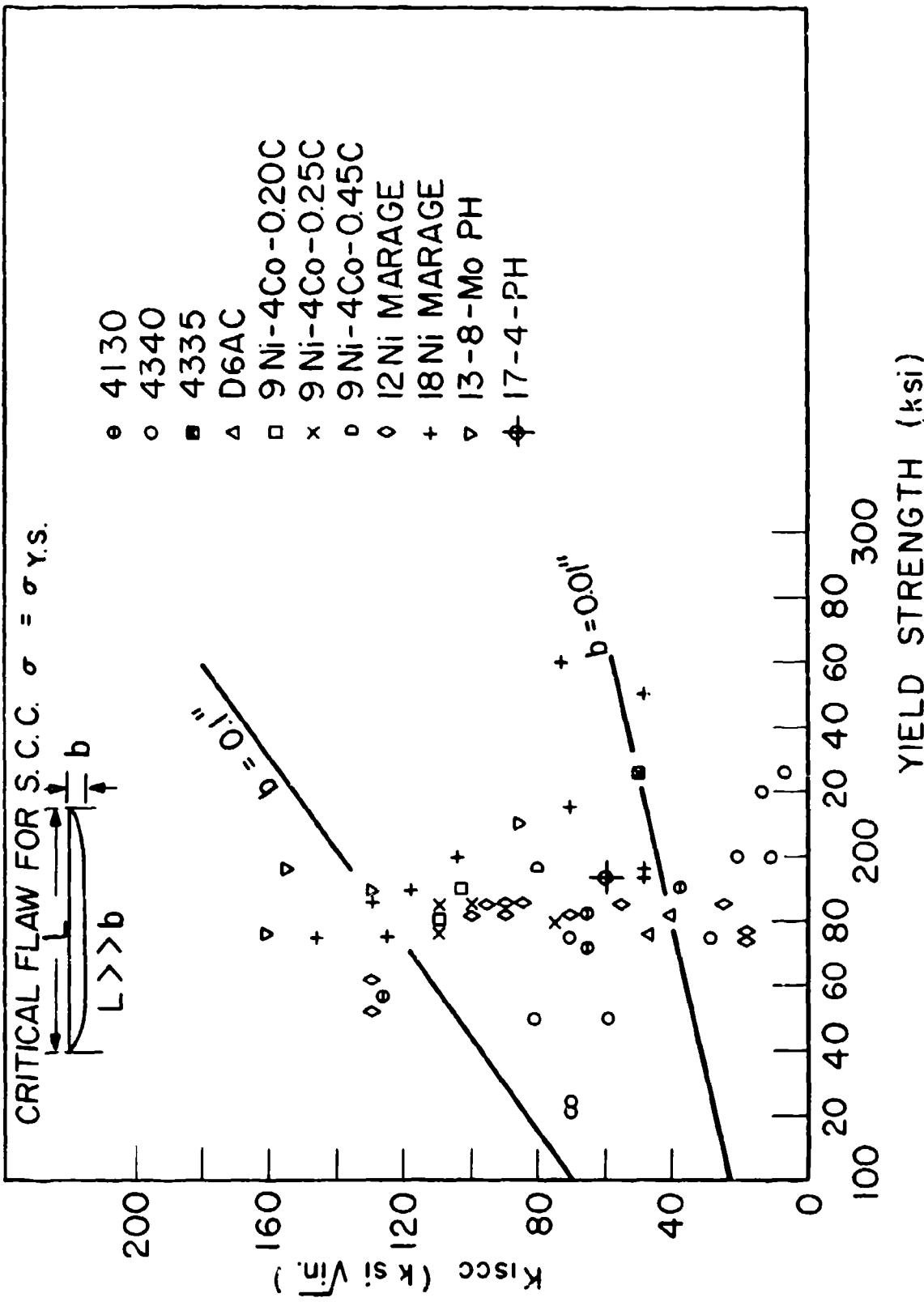
Fig. 8 - Threshold stress intensity values for stress-corrosion crack propagation in salt water of some commercial steels.

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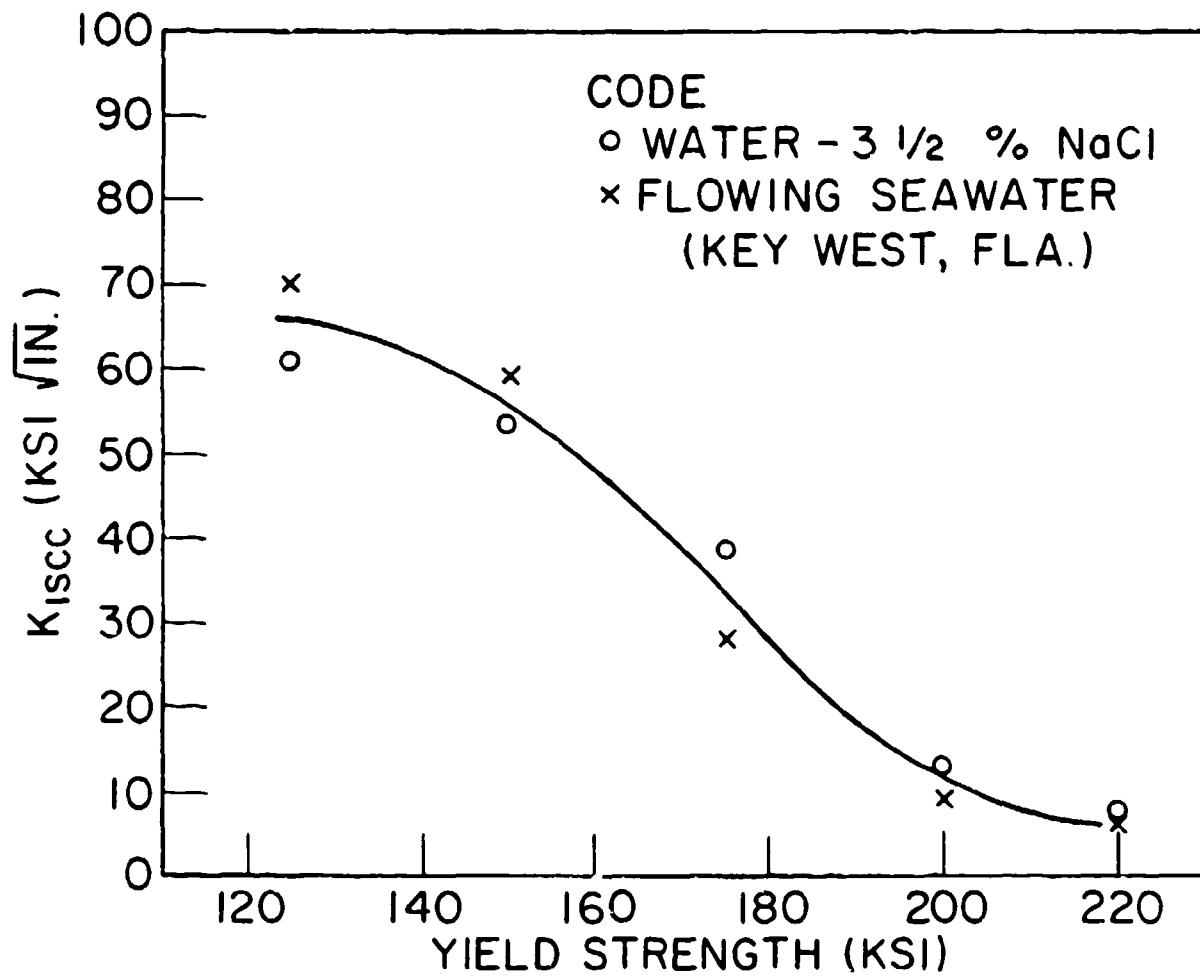
Fig. 9 - Effects of quiescent distilled water containing 3 1/2 percent NaCl and flowing seawater on the threshold stress intensity parameter for stress-corrosion cracking of AISI 4340 steel.
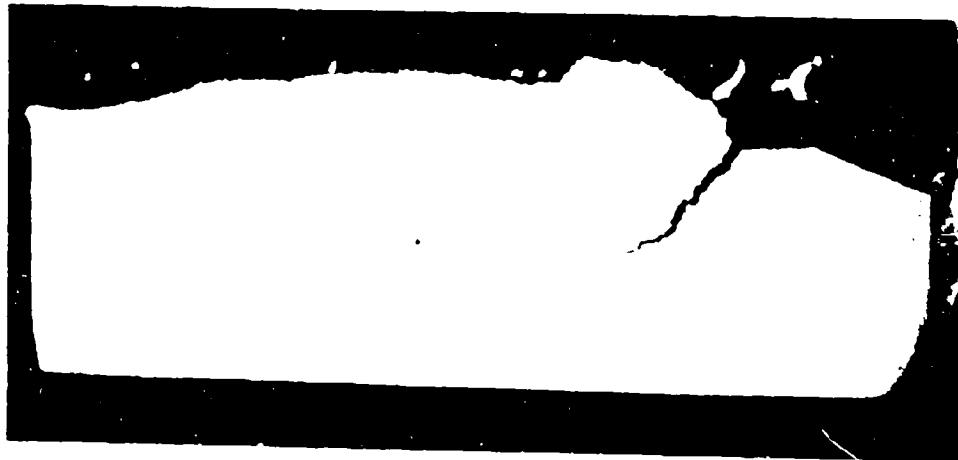
Fig. 10 - Crack branching in 9Ni-4Co-0.2C steel. Lower photo
is a section through the center of a specimen. Approximately
4X . magnification.
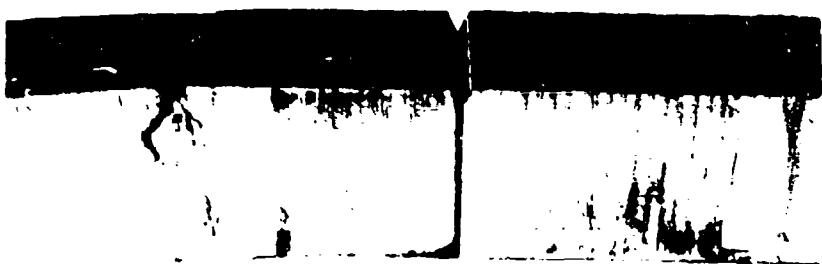
Fig. 11 – Cracking in 13Cr-8Ni-Mo-PH steel at junction of polyethelene container and specimen. Note unaffected notch area with fatigue crack.
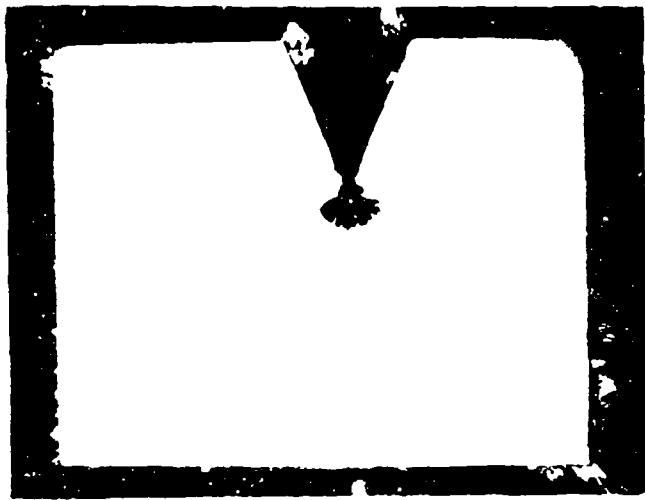
Fig. 12 – Cross section of the precrack of a specimen of 12Ni-5Cr-3Mo maraging steel loaded in steps to a nominal stress intensity value of 170 ksi$\sqrt{\text{in.}}$ over a period of 3000 hours.
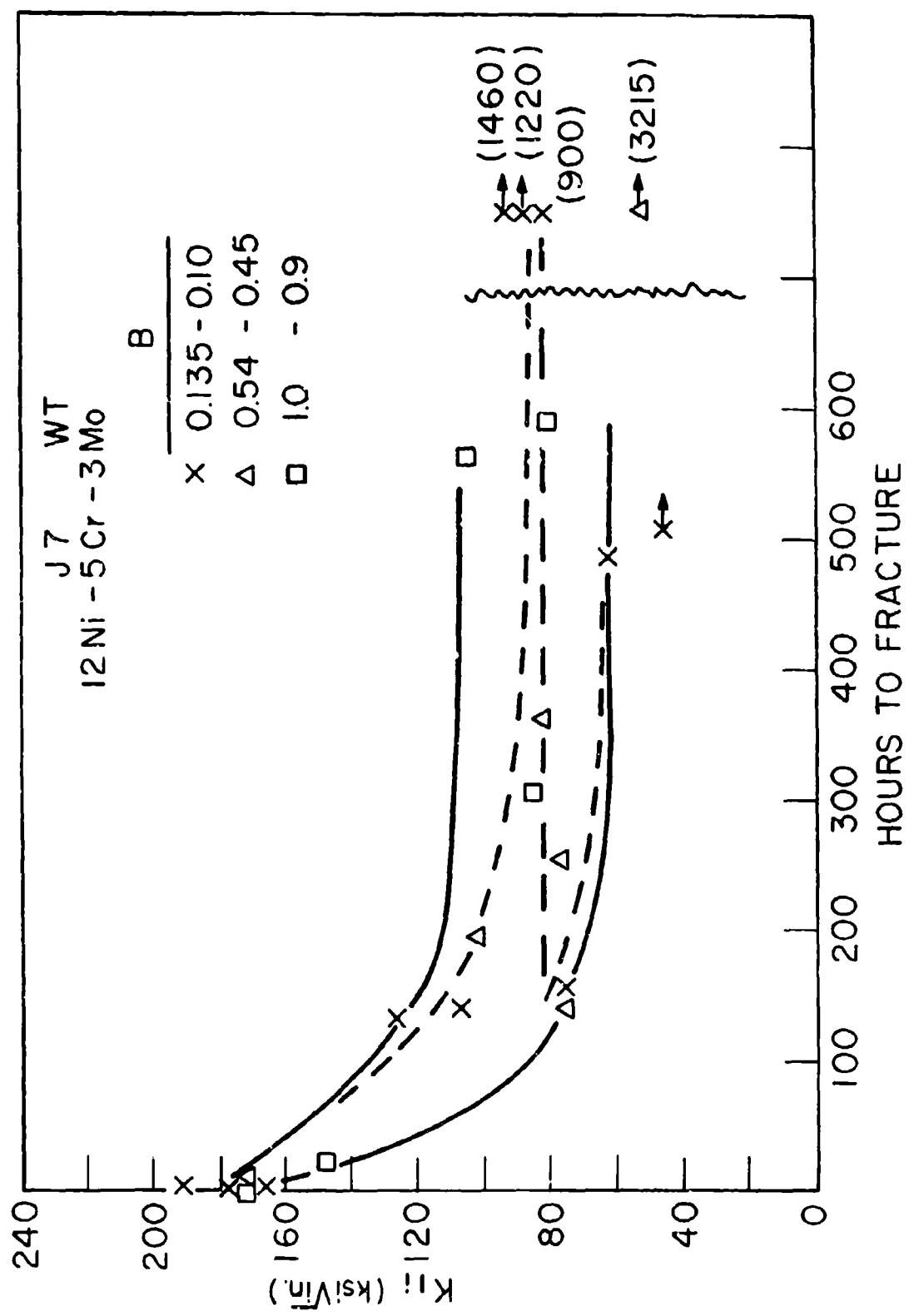
Fig. 13 - Effect of specimen breadth B on the time to rupture of specimens of 12Ni-5Cr-3Mo maraging steel at various values of stress intensity in salt water. Dotted lines indicate maximum in time to fracture at intermediate stress intensity level.

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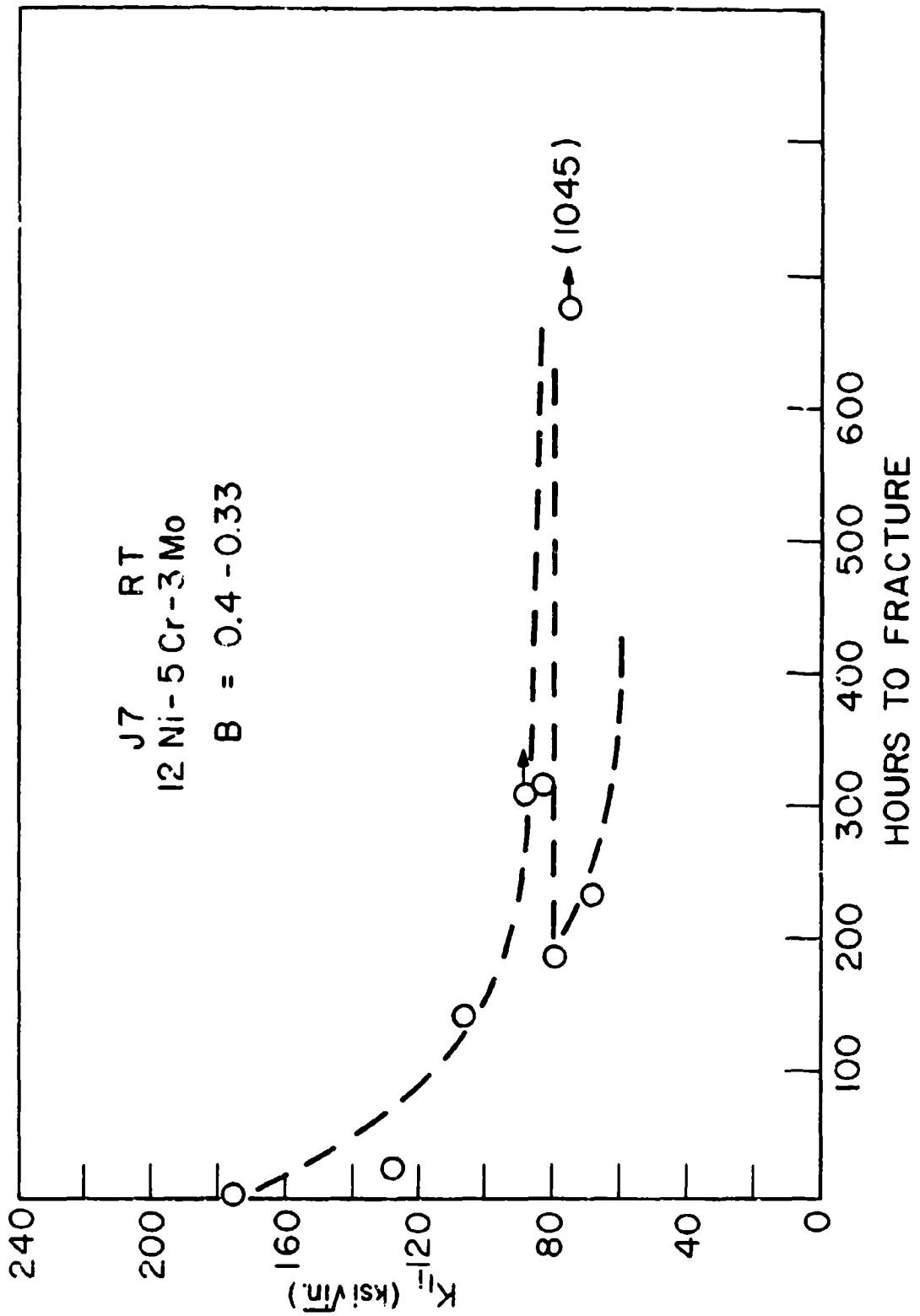
Fig. 14 - Effect of stress intensity on the time to fracture of specimens of 12Ni-5Cr-3Mo maraging steel in salt water. Dotted lines indicate the time reversal at intermediate stress intensity level.

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